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Novel rotor design for high-speed flux reversal motor

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Abstract

A single-phase Flux Reversal Machine for high speed applications has a reliable rotor and a good specific power. This paper shows that eliminating the regions of negative torque of this machine can be reached if an asymmetric rotor is used. This machine with an asymmetric rotor was compared with that with a symmetric rotor. In the rated loading mode, the calculated torque ripple of the flux reversal machine with the symmetric rotor is 297%, while that of the one with the asymmetric rotor is 185% which is less by 1.6 times. The proposed high-speed flux reversal machine with the asymmetric rotor can be applied in low-cost drives of household appliances (vacuum cleaners, hand dryers, blenders, washing machines) and in electric power hand tools (angular grinders, miter saws, drills) to replace single-phase synchronous motors or single-phase Hybrid Switched Reluctance Motors.

Keywords: Electrical machinery; Flux reversal machines; High-speed electrical machines; Mathematical modeling; Single-phase motors

1. Introduction

Low-cost single-phase permanent magnet synchronous motors are used in low-power applications of variable speed. The frequency converters of single-phase motors are simpler and cheaper than that of three-phase motors. However, the starting torque of single-phase machines is low. Therefore, they are used in fans, compressors, pumps, vacuum cleaners and other household appliances not requiring a high starting capability.

The main drawback of single-phase synchronous motors is their torque ripple much higher than that of three-phase motors. Thus, the torque ripple of the former motors can be up to 168% in [1] while that of the latter motors is usually less than 10%.

In high-speed applications, such as blowers, vacuum cleaners and turbochargers, the rotors of synchronous motors with permanent magnets on the rotor are designed with a retaining ring to withstand centrifugal stress and to ensure rotor durability, which increases the rotor complexity and cost. Furthermore, the equivalent air gap (the distance between the stator teeth and the permanent magnets) increased due to the retaining ring results in a decrease in the efficiency and the specific torque.

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Nomenclature

DC–AC	Direct current to alternating current
FEM	Finite element method
FRM	Flux Reversal Machine
HSRM	Hybrid Switched Reluctance Motor
A_z, V s m^{-1}	Vector magnetic potential (projection on the axis z perpendicular to the plane of the calculated area)
h_{mag}, mm	Thickness of the magnets
R_r, mm	Rotor outer radius
R_s, mm	Stator outer radius
R_{bs}, mm	Stator slot bottom radius
R_{br}, mm	Rotor slot bottom radius
s, mm	Radial length of the chamfered tooth area
W_{op}, mm	Stator slot opening width
Z_r, mm	Rotor tooth thickness (symmetric rotor)
Z_{r1}, mm	Width of the rotor surface adjacent to the air gap (asymmetric rotor)
Z_{r2}, mm	Overall width of the rotor (asymmetric rotor)

As a replacement to the single-phase synchronous machines with magnets on the rotor, motors with a rugged and reliable toothed rotor are considered for the high-speed applications. One of these motors is a single-phase Hybrid Switched Reluctance Motor (HSRM) with magnets fixed on the stator developed for a blender and described in [2]. In contrast to synchronous motors with magnets on the rotor, the HSRM has a simple toothed rotor without any magnets. The torque ripple of the single-phase HSRM [2] is 168%, and its torque is of constant sign throughout the entire electric period.

Although HSRMs have significant benefits over traditional synchronous single-phase motors, its disadvantage is that it is supplied by unipolar current, while traditional synchronous motors do by the bipolar AC current. As a result, to reach the same peak-to-peak sweep of the HSRM stator current, its maximum and root mean square (RMS) values need to be significantly higher. Besides, the cost and the size of the frequency converter for the HSRM, as well as the power losses in the converter and in the stator winding increase.

Single-phase Flux Reversal Machines (FRMs) also being motors with magnets on the stator and with toothed rotor have similar benefits over traditional synchronous motors. Moreover, like traditional synchronous motors with magnets on the rotor, FRMs are supplied by bipolar current, which increases the peak-to-peak current sweep at given its maximum and RMS values, compared to the HSRM [3]. These decrease losses in the winding, increase the motor efficiency, and decrease the cost and the size of the FRM DC–AC converter [3].

A few designs of a single-phase FRM are described at the moment. The earliest design of a single-phase FRM was described in [4]. The motor has two stator teeth and three teeth on the rotor. Permanent magnets forming two poles are located on each of the stator teeth. However, there is an unused space between the stator teeth, which significantly reduces the motor specific characteristics. Also, the lifetime of the bearings decreases due to the radial force arisen from the asymmetry of the motor structure. These problems of the FRM [4] were resolved by another single-phase FRM described in [5] (Fig. 1b).

However, all known single-phase FRMs described in [3–6] have the region of negative torque in the machine cycle, and their torque ripple is not less than 290%. Therefore, developing a single-phase FRM with the torque not changing its sign and with reduced torque ripple is demanded and novel.

This paper demonstrates that eliminating the intervals of negative torque is possible in the FRM of design [3,6] if an asymmetric rotor is used. The characteristics of the single-phase FRM with the symmetric rotor and that with the novel asymmetric rotor are compared for the case of high-speed applications. Both configurations are intended to use in low-power household devices (the rated rotational speed is 18 000 rpm, the rated loading torque is 0.4N m, the rated shaft power is 750 W).

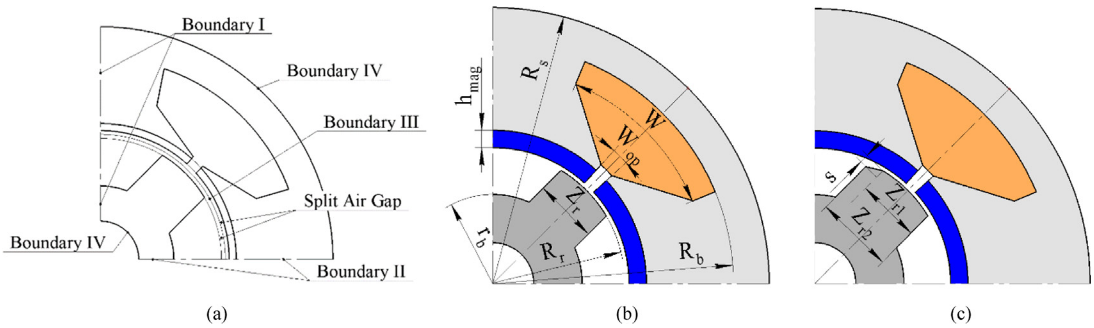


Fig. 1. (a) Structure of the calculated area; (b) the main geometric parameters of the FRMs; (c) additional geometric parameters of the new asymmetric rotor of the FRM.

In the paper, it is demonstrated that the torque waveform of the FRM with the symmetric rotor has two intervals with negative torque while the torque of the FRM with the asymmetric rotor is always positive in the rated mode. The calculated torque ripple of the FRM with the symmetric rotor is 297%, while that of the FRM with the asymmetric rotor is 185% which is less by 1.6 times.

2. Brief description of the 2-D FEM mathematical model of the single-phase FRM

For calculating the FRM performances, a 2-D FEM (finite element method) mathematical model with reduced computational time was developed [7]. The magnetic field and magnetic flux density are supposed to lie in the plane of the motor cross-section. The winding current and the electric fields is supposed to be perpendicular to this plane. Elmer software is applied to solve this FEM problem. In this model the voltage waveform is supposed to be rectangular. Winding and core losses are neglected in the stage of solving boundary problems and are taken into account in post-processing. By integrating the rectangular voltage, the trapezoidal flux waveform can be found. The rotor speed is supposed to be constant during the machine cycle. So, the flux and the rotor position are known at any time. Only for these flux and rotor position the boundary problems should be solved. In other words, in the developed mathematical model the set of the boundary problems corresponding the machine cycle is only to be solved and considering all possible combinations of the rotor position and the current is not required.

The structure of the boundary problems to be solved was also described before [5]. The calculated area is split into two subareas corresponding to the rotor and the stator by Boundary III (Fig. 1a) which allows considering the rotor and the stator in their own reference frames. So, one and the same geometry is used for all boundary problems and the total time derivative of the magnetic flux density becomes exactly the same as the partial time derivative which significantly simplifies the core and magnet losses calculation in the postprocessing.

The FRM is symmetric with respect to its rotation by 90° and changing the current and magnetization directions. Therefore, considering only quarter of the FRM is sufficient. The Boundaries I and II are joined with aperiodic boundary condition where the vector magnetic potential changes its sign.

The calculated area is divided into two subareas by boundary III so as the rotor and the stator are considered in their reference frames. The boundary condition joining subareas on boundary III depends on rotor position and takes into account the rotor position. On the Boundary IV, the boundary condition for magnetic vector potential $A_z = 0$ is assigned.

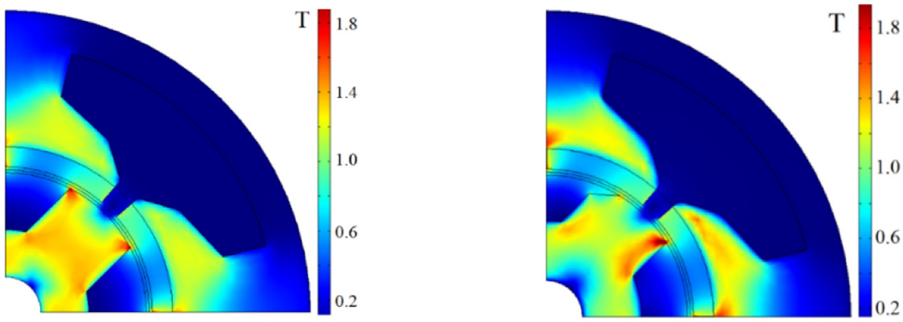
Also, the FRM and its operating mode are symmetric in respect to the rotor rotation by 90° which allows considering the rotor positions only from the 90° interval. A more detailed description of the mathematical model is not provided in this paper because of a limit for the paper volume.

3. The Results of Mathematical Modeling of Two FRMs and Discussion

The 2D FEM mathematical model of the FRMs used is described in papers [7]. Two single-phase FRMs with the following parameters were compared in this paper: the rated mechanical power is 750 W, the rated speed is 18 000 rpm. Their main geometric parameters are shown in Fig. 1b and c. Their values are as follows: the outer stator radius R_s is 25.5 mm, the stator slot bottom radius R_{bs} is 22.5 mm, the stator slot width W is 61°, the stator slot opening width W_{op} is 8°, the thickness of the magnets h_{mag} is 1.7 mm, the air gap is 0.5 mm, the rotor outer radius R_r is 11.8 mm, the rotor slot bottom radius R_{br} is 8 mm , the stack length is 30 mm.

The detailed investigation of the single-phase FRM with the symmetric rotor is described in [3]. Its rotor tooth thickness Z_r of 7.2 mm is also shown in Fig. 1b. The new asymmetric rotor of the single-phase FRM is shown in Fig. 1c. To avoid the negative values in the torque waveform, the following dimensions of the rotor are chosen: the radial length of the chamfered tooth area s is 2 mm; the width of the rotor surface adjacent to the air gap Z_{r1} is 5.5 mm; the overall width of the rotor Z_{r2} is 7.5 mm.

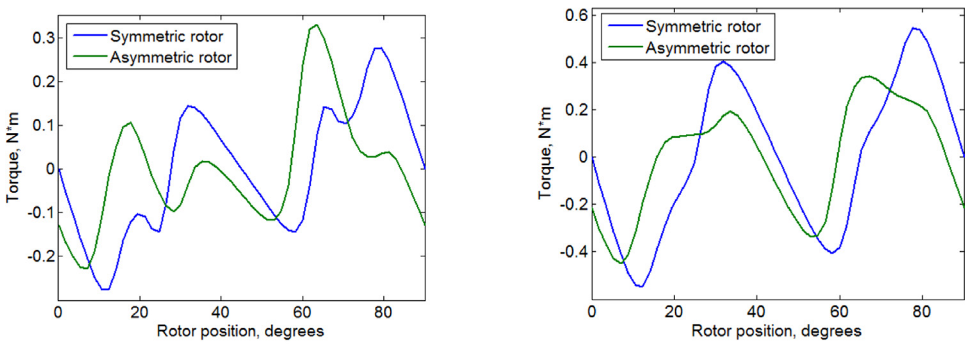
The characteristics of the single-phase FRMs with the symmetric and asymmetric rotors were calculated on the basis of the FEM. Fig. 2 shows the magnetic flux density in both FRMs at zero winding flux and at zero rotor position that is when the middle of the rotor surface adjacent to the air gap is over the middle of the slot opening. In the case of the symmetric rotor, the flux density plot is symmetric as well. This position is an equilibrium position in the case of the symmetric rotor. In the case of the asymmetric rotor, the flux density is concentrated on the right side of the rotor tooth. In this case, the equilibrium position is shifted clockwise.



(a) (b)

Fig. 2. Plots of the magnitude of flux density (T) in the FRM: (a) symmetric rotor; (b) asymmetric rotor.

Fig. 3a shows the cogging torque waveforms when the winding is open. It can be observed the amplitude of the cogging torque is even higher in the case of the asymmetric rotor. Thus, one might expect that the torque ripple is also higher in this case and eliminating the periods of negative torque using the asymmetric rotor design cannot be reached. However, Fig. 3b demonstrates the torque ripple waveform at the short-circuited stator winding. Its peak-to-peak value of the FRM with the symmetric rotor is 1.09 N m while that of the FRM with the asymmetric rotor is 0.79 N m, which is lower by 27%. In addition, in the vicinity of 22.5 and 67.5 degrees, significant areas with positive torque values can be observed in the case of the asymmetric rotor.



(a) (b)

Fig. 3. The cogging torque dependencies on the rotor position: (a) at open winding; (b) at short-circuited winding.

Fig. 4a shows the stator current dependence on the rotor position at the short-circuited winding. Comparing Fig. 3b and Fig. 4a, it can be concluded that crossing zero by the torque and current waveforms is shifted to the left in the case of the asymmetric rotor. However, this effect is more apparent for the torque waveforms. The voltage at

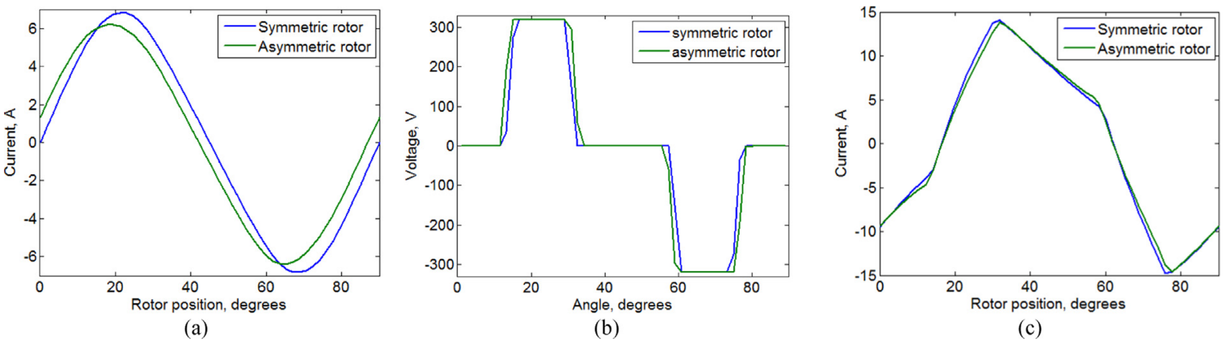


Fig. 4. The FRM waveforms versus the rotor position: (a) stator current at the short-circuited winding; (b) voltage in the rated loading mode; (c) stator current waveforms in the rated loading mode.

the rated mode obtained by differentiating the flux numerically is show in Fig. 4b. The flux waveform is not quite trapezoidal, and the form of the voltage pulses is not quite rectangular because of discretization. It can be seen that the voltage switching moments and the duty cycles are slightly different to obtain the same rated power for both designs. Fig. 4c shows the waveform of the current in the rated mode.

The single-phase FRM is driven by rectangular voltage pulses of various signs, using the rotor position feedback. The duty cycle of the pulses varies with load. The term "duty cycle" is used to designate the fraction of the electrical period which is filled by voltage pulses of any polarity. The greater the loading torque, the larger the duty cycle. The magnitude and the RMS value of the current also increase when the voltage duty cycle is increased.

Fig. 5a shows the dependencies of the torque on the rotor position for both considered FRMs in the rated mode.

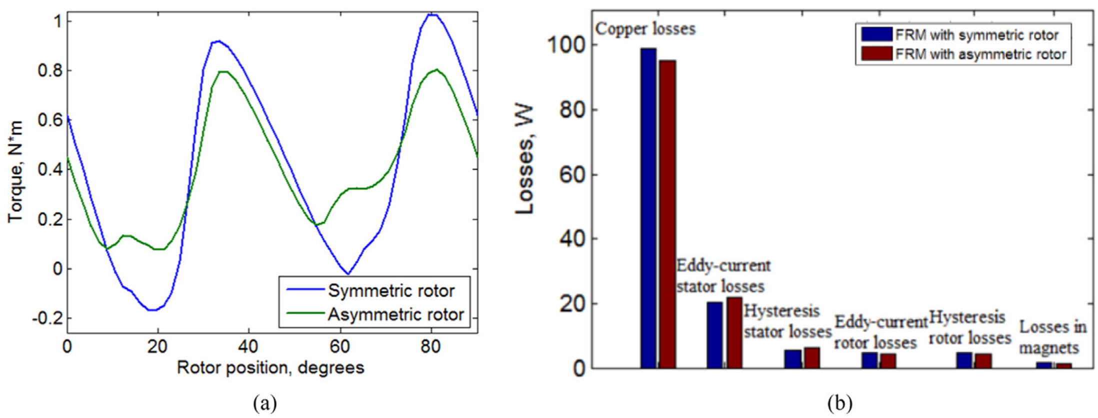


Fig. 5. (a) the torque waveforms versus the rotor position in the rated loading mode; (b) the losses in the rated loading mode.

It is shown in Fig. 5a that the torque waveform of the FRM with the symmetric rotor has two intervals with negative torque in the vicinity of 22.5 and 67.5 degrees while that of FRM with the asymmetric rotor has no negative values. Besides, the torque ripple of the FRM with the symmetric rotor is 297%, while that of the FRM with the asymmetric rotor is 185% which is less by 1.6 times. The losses in both FRM designs at the rated mode are shown in Fig. 5b. Decreasing the torque ripple and eliminating the negative torque regions are obtained without losing the motor efficiency. In the case of the asymmetric rotor, the total losses became even 2.7% lower.

In this study, the FRM was designed without using optimization methods. Therefore, the performances of the proposed FRM can be improved. In future works, it is planned to optimize the design of the FRM with the asymmetric rotor using a genetic algorithm or Nelder–Mead method, as it is described in [5].

The proposed high-speed single-phase FRM with the asymmetric rotor can be applied in low-cost drives of household appliances (vacuum cleaners, hand dryers, blenders, washing machines etc.) and in electric power hand tools (angular grinders, miter saws, drills etc.) to replace the single-phase synchronous motors or the single-phase Hybrid Switched Reluctance Motors.

4. The conclusion

A design of a single-phase FRM for high-speed applications with the asymmetric rotor was carried out in the paper to eliminate the moments of negative torque in the torque waveform. Its performance was compared to the single-phase FRM with the symmetric rotor. The torque waveform of the FRM with the symmetric rotor has two intervals with negative torque while the torque ripple of the FRM with asymmetric rotor is always positive. In the rated mode, the calculated torque ripple of the FRM with the symmetric rotor is 297%, while that of the FRM with the asymmetric rotor is 185% which is less by 1.6 times.

The proposed high-speed single-phase FRM with the asymmetric rotor can be applied in low-cost drives of household appliances (vacuum cleaners, hand dryers, blenders, washing machines etc.) and in electric power hand tools (angular grinders, miter saws, drills etc.) to replace the single-phase synchronous motors or single-phase Hybrid Switched Reluctance Motors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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